GAS PRESSURE LOADS FROM EXPLOSIONS WITHIN VENTED AND UNVENTED STRUCTURES

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ABSTRACT

Gas pressures from explosions within enclosures, as opposed to shock loads, can be the dominant loads causing structural failure. This paper reviews test results and prediction methods for gas pressures for many types of internal explosions including high explosives, high explosives plus combustibles, gas mixtures and dust suspensions.

INTRODUCTION AND BACKGROUND

For explosions in enclosures involving high explosives, solid propellants, high explosive with combustible materials in contact, or combustible mist, dust, or gaseous explosive mixtures, the long-duration gas pressures caused by confinement of the products of the explosions can be the dominant loads causing structural failure. These quasi-static pressures are determined by the total heat energy in the explosive and/or combustible source, the volume of the enclosure, the vent area and vent panel configuration, the mass per unit area of vent covers, and the initial ambient conditions within the enclosure.

Previous analytic work, similitude analysis, and numerous experiments have addressed several aspects of this problem and provided a good data base for more general predictions. Ref. 1 collates much of this information for gas pressure parameters for bare high explosive detonations in enclosures with open vents, while Ref. 2 includes analytic predictions of these parameters for similar explosions with covered vents with various masses per unit area. Maximum pressures for gas and dust combustible mixtures initiated in unvented and vented enclosures are reported in Ref. 3 and 4. Most recently, test data for gas pressures in a sealed structure from high explosives surrounded by combustible liquids and solids are reported in Ref. 5.

Tests of solid propellants burned in vented structures are reported in Ref. 6 and 7. Ref. 6 also includes derivation of a scale modeling law for pressures for this situation. Scale modeling of dust and gas explosions in enclosures is inherent in work in Ref. 3, while a more thorough law for vented dust explosions appears in Ref. 8.

In this paper, the authors will review the literature and present methods for predicting internal gas pressure loads under the following conditions: 1) bare high explosive detonations in structures with open vents, 2) high explosive plus combustible explosions in closed structures, and 3) gas and dust explosions in closed and vented structures. The predictions will be based on graphs and/or numeric fits to scaled parameters from appropriate similitude analyses.

GAS PRESSURES FOR INTERNAL HE EXPLOSIONS

The loading from an explosive charge detonated within a structure consists of two phases. The initial phase consists of several high amplitude, short duration, reflected pressure shocks. This phase of the loading is very geometry dependent, with the highest loads generally occurring on the surfaces nearest the charge. On each reflection, the shock strength is attenuated until at some point the internal pressure has settled to a slowly decaying level. This is the quasi-static pressure loading phase. This phase is characterized by essentially uniform pressures throughout the structure at any point in time. The rate of quasi-static pressure decay is a function of the vent area, structure volume and the nature of the explosive source.

A typical pressure trace obtained during an internal explosion in a vented structure is shown in Figure 1. Traditionally (Ref. 9), the peak quasi-static pressure is established by fitting a smooth line through the data beginning at the end of the pressure trace and extending back towards time zero, the time of charge ignition. This line is shown in Figure 1 as a solid line. The peak P_{qs} is then taken as the intersection of the fitted line and a vertical line at time zero (shown as a dotted line in the figure). This point is labeled A in Figure 1. For a vented structure, a more appropriate technique has been suggested (Ref. 1, 5). This method is applied by drawing a ramp increase in pressure extending from time zero, which follows the base of the pressure shocks. This line is shown as a dashed line in Figure 1. The intersection of the ramp pressure increase with the line fitted through the pressure decay is the peak quasi-static pressure. This point is labeled B in the figure. For explosions inside sealed enclosures, points A and B will have nearly the same ordinates, whereas for explosions with increasing vent areas, the difference in ordinates between points A and B increases.

In Ref. 1, a very complete analysis of gas pressures from internal explosion data was presented. The authors performed a similitude analysis to
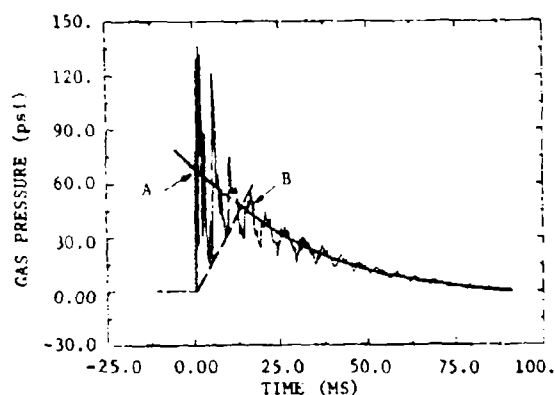
Figure 1. Typical Pressure Record from an Internal Explosion in a Vented Structure

Figure 2. Peak Quasi-Static Pressure as a Function of the Charge Weight to Enclosure Volume

determine the functional form of the quasi-static pressure, as a function of the physical parameters pertaining to the problem of an internal explosion inside a vented structure. Based on this analysis, the following equation was derived:

Peak Quasi-Static Pressure:

$$\log \overline{P}_{QS} = 0.30759 + 0.51815 \log (W/V) - 0.150534 [\log (W/V)]^2 + 0.31892 [\log (W/V)]^3 + 0.10434 [\log (W/V)]^4 - 0.14138 [\log (W/V)]^5 + -0.019206 [\log (W/V)]^6 + 0.021486 [\log (W/V)]^7 \quad (1)$$

Equation (1) was the result of curve fits to 177 experiments. Figure 2 presents the curve fit together with the measured data. One approximation was made in the analysis of the test data. The explosive energy contained in any high explosive is directly proportional to the explosive mass. As it turns out, the charge energy-to-explosive mass ratio for most explosives is nearly the same. For convenience, the analysis performed in Ref. 1 utilized the charge mass, rather than the charge energy.

Based on the results of the analysis of the internal explosion data, the authors of Ref. 1 found that the peak quasi-static pressure was independent of the vent area, but dependent on the charge weight-to-structure volume ratio.

GAS PRESSURES FOR HE PLUS COMBUSTIBLES

Recently (Ref. 5), a series of experiments was conducted in which various combustible materials were placed in varying degrees of contact with high explosive charges. The object of the tests was to determine whether the combustible materials could contribute to the quasi-static pressure development within a sealed enclosure. The combustible materials investigated in this effort are listed in Table 1. In every case, the high explosive was 0.992 lb of PBX-9404. All of these experiments were conducted in the same enclosure, so the only parameter not held constant was the combustible
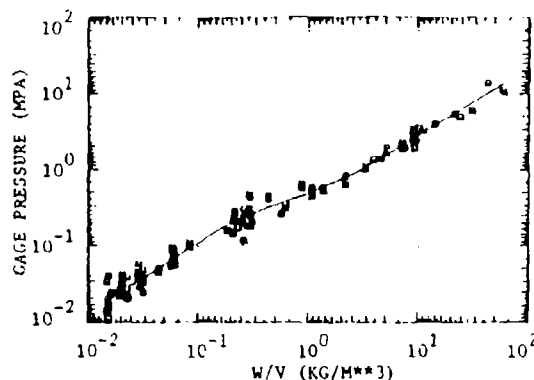
Table 1. Combustible Materials and Configurations Tested*

Series	Material	Configuration
1	Polycarbonate	A 67.6 gm polycarbonate disk was attached to the end of a cylindrical ($i/d=1$) charge.
2	Polycarbonate and Aluminum	A 135 gm aluminum casing surrounding the side of a cylindrical charge. A polycarbonate disk covered one end of the charge.
3	50/50 Mix of DMF and Acetone	A spherical charge was submerged in 5 oz of the fluid.
4	Polycarbonate	Two polycarbonate hemispheres were attached to opposite poles of the charge. The total polycarbonate weight was 48.25 gm.
5	50/50 Mix of DMF and Acetone	Five 1 oz containers of the fluid were equally spaced on a circle 36 in. in diameter around the charge.
6	Low density polyethylene	Polyethylene beads suspended in an epoxy base, and formed into a four-sided box, centered on the charge. The weight of the box was 273 gm.

*The explosive was 0.992 lb of PBX-9404. Test Series 1 and 2 utilized cylindrical charges, while the remaining tests utilized spherical charges. The charge location was the same in all experiments.

configuration. Note that the P_{QS} for a bare 0.992 lb PBX-9404 charge is 48.7 psi. In every case, the addition of combustible materials in near contact with the HE charge increased the quasi-static pressure, in some cases dramatically.

The degree of quasi-static pressure enhancement produced by a combustible is related to the heat energy content of the material. This is shown in Figure 3 where the excess P_{qs} (the P_{qs} produced by the combustible plus the HE, less the P_{qs} produced by the HE alone.) is plotted as a function of the combustible energy content. The combustible energy content is defined as the mass of combustible times the appropriate heat of combustion from Table 2. As seen in Figure 3, the enhancement in the quasi-static pressure increases uniformly with increasing combustible energy, as long as the combustible is in intimate contact with the charge. The only point not following the general trend of the data corresponds to the series of tests in which the combustible fluid was dispersed a large distance from the charge.

The phenomenon of quasi-static pressure enhancement produced when combustible materials are placed near HE sources has only been recently discovered. The effect has been observed for a variety of combustible materials, but no variations in charge to combustible mass, charge type, structure volume, or degree of venting have been tested. The implications of the data accumulated so far are that quasi-static loading calculations should include estimates of contributions from the burning of combustible materials whenever such materials are expected to be in intimate contact with HE sources.
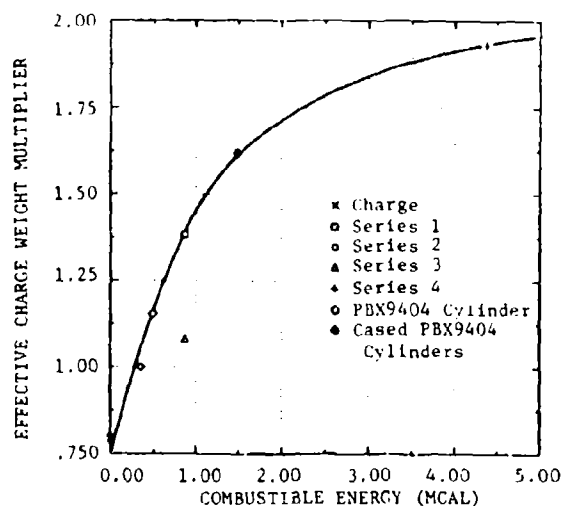

Figure 3. Excess Quasi-Static Pressure (psi)

GAS AND DUST EXPLOSIONS IN CLOSED AND VENTED CHAMBERS

Many accidental explosions occurring in industry involve the ignition within enclosures of combustible mixtures of gases with air, or suspensions of combustible dusts in air. Such mixtures ignited in the open do not cause blast waves or significant pressure waves, but instead generate only transient fireballs as flame fronts progress at rather low rates (meters per second) through the combustible mixtures.

But, when the combustible mixtures are ignited inside a sealed or vented enclosure, the confinement provided by the enclosure can allow significant pressure rises which can disrupt the structure. A typical pressure history for such an explosion within an unvented enclosure is shown in Figure 4.

The maximum rate of pressure rise $\frac{dp}{dt}$, and the maximum pressure P_m are determined by the reactivity of the particular material, the fuel-air ratio, the amount of material, and the volume of the enclosure. When the enclosure has a vent area, covered by a vent designed to open at pressure P_u, the pressure-time history is modified as shown in Figure 5. The amplitudes and times of the maxima P_1 and P_2 are functions of the gas flow dynamics through the vent, and either P_1 or P_2 may be the maximum pressure.

Table 2. Heat of Combustion for the Various Combustible Test Materials

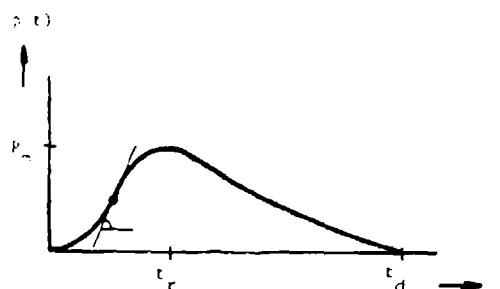| Material	Heat of Combustion (cal/gm)
PBX-9404	2369
Polycarbonate	7223
Acetone	7363
DMF	6259
Polyethylene	9400
Aluminum	7400

Figure 4. Schematic Overpressure-Time History in Confined Gas or Dust Explosions (Ref. 10)
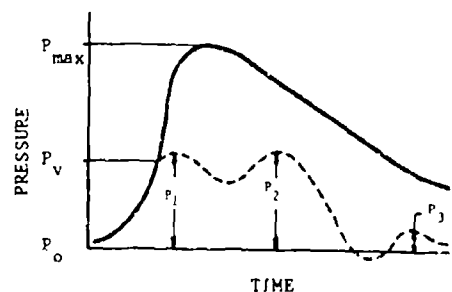

Figure 5. A Representation of a Pressure-Time History of an Unvented (Curve A) and Vented (Curve B) Deflagrative Explosion (Ref. 13)

The voluminous data and analyses in the literature (see Ref. 10) on the characteristics of these pressure histories can be condensed and presented in compact form based on similitude analyses

179

(Ref. 6 and 7). Bradley and Micheson (Ref. 11 and 12) present scaled upper limit curves for gas explosions in vented vessels. These are reproduced here as Figures 6 and 7. In these figures, the dimensionless terms are

$$\bar{A} = \frac{AK_d}{A_s} \quad , \quad \dot{S}_o = \frac{U}{a_o} \quad , \quad \bar{P}_m = P_m/p \qquad (2)$$

where A is vent area, A_s internal surface area, K_d discharge coefficient ($\div 0.6$), U is gas velocity ahead of a flame front, a_o is ambient sound speed, P_m is maximum pressure and p_o is ambient pressure.
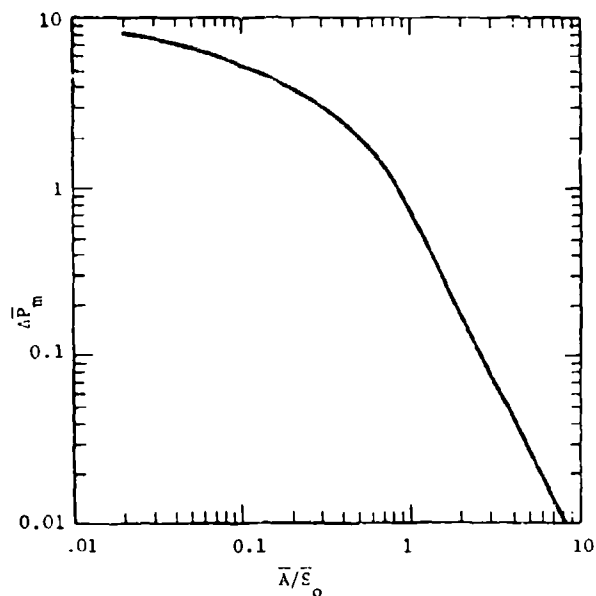
Figure 6. Safe Recommendations for Uncovered Vent Areas, Gaseous Explosions (Ref. 12)

For dust explosions, maximum pressures are also a function of the dust reactivity, and a scaled vent area. Figure 8 shows scaled plots of $\bar{P}_m$ for dusts of increasing reactivity, ST1 through ST3. Here $\bar{A}$ is defined somewhat differently, as

$$\bar{A}_v = (A/V^{2/3}) \qquad (3)$$

where V is volume of the enclosure.

In either gas or dust explosions of this nature, the dimensionless maximum pressure rate for a given combustible mixture is

$$\dot{\bar{P}} = (\dot{P} \, V^{1/3}/a_o p_o) \quad . \qquad (4)$$

This scaling is consistent with Bertknecht's "cube-root law." (Ref. 3)

Figure 7. Safe Recommendations for Covered Vent Areas, Gaseous Explosions (Ref. 12)

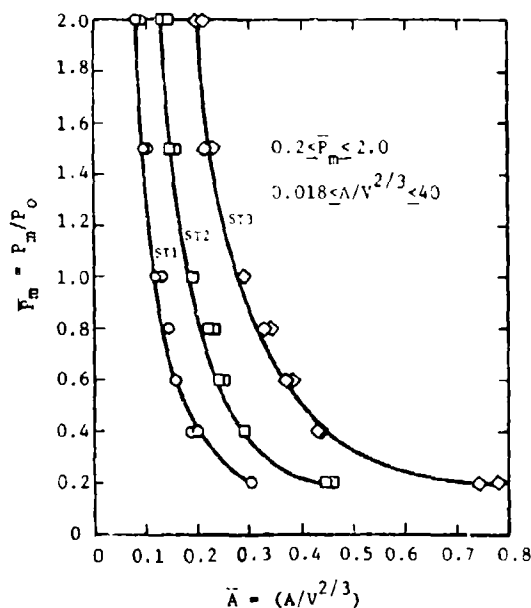$$0.2 \le \bar{P}_m \le 2.0$$
$$0.018 \le A/V^{2/3} \le 40$$

Figure 8. Scaled Maximum Pressures for Dust Explosions Versus Scaled Vent Area Ratio (Ref. 10)

It is also clear from Ref. 11 and 12 that the maximum pressures attainable within enclosures for gaseous explosions are remarkably constant for all

combustible gases, varying from about 8 atmospheres for natural gas to only 10.25 atmospheres for acetylene.

CLOSURE

Even though the material on gas pressures for explosions within enclosures which is summarized in this paper shows an extensive experimental and analysis base, there are still a number of significant data gaps which limit our ability to predict these pressures. These include at least:

o   Lack of data on pressures generated by HE-combustible combinations

o   Lack of data and validated analytic methods for effects of vent cover parameters for HE explosions

o   Lack of data for mixtures of combustible gases and dusts

o   Lack of data for dust explosions in real configurations, such as grain elevator galleries.

o   Lack of data for effects of vent cover parameters for gas and dust explosions.

Not all of these gaps are important to weapons effects analysts, but all are quite important in the explosives safety community.

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